MULTISTAGE GAS TRIGATRON FOR MEGAVOLT OPERATION

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Abstract

A multistage, command-fired, trigatron switch, intended for megavolt operation, has been designed, constructed, and tested. The gas switch incorporates a uniform field geometry, to lower pressure-gap spacing requirements; a unique cascading trigger scheme, to reduce closure jitter; and carbon electrode inserts, to lengthen operating lifetime. This paper presents the analysis used to determine switch jitter requirements, a description of the switch design, the switch tests performed and a summary of the results.

I. Introduction

Switch performance is primarly responsible for power amplification, and has always been a key element in pulsed power system design. Typically, high power, high voltage switching has been accomplished with liquid dielectric breakdown, a technique which suffers from high energy losses[1,2] and poor control of switch closure timing (i.e., jitter). Both deficiencies become increasingly punitive as pulsed power system designs attempt to achieve higher power levels.

This paper describes the design and preliminary testing of a multistage, gas-dielectric, trigatron switch which is intended to reduce both energy loss and jitter. To date, the switch has been tested to 185 kilovolts per stage (1.1 MV across six stages) with peak currents of 130 kiloamps and a total charge transfer of 0.5 coulomb. In principle, if uniform voltage sharing can be achieved between stages, the operating voltage of a multistage switch can be scaled by selecting the appropriate number of stages.

Section II describes the analysis performed to quantify the switch jitter requirements for a given application. A discussion of the key features of the multistage trigatron switch is presented in section III. A description of the switch test configuration and a summary of the results achieved to date is given in section IV.

II. Switch Jitter Analysis

In pulsed power systems which combine multiple outputs of several pulse forming elements into a single load, the need for pulse arrival synchronization is usually critical. Knowledge of how the synchronization requirement imposes jitter specifications on the controlling output switches is of considerable importance in switch design. For the purpose of making a quantitative evaluation of switch jitter requirements, we have chosen a system model of N parallel pulse forming elements, each controlled by a single switch. It is further assumed that the N switches are identical (i.e., have the same jitter characteristics) and completely control the power pulse arrival time at the load. We establish the criterion that a successful event is one in which all the energy pulses arrive at the load in an interval of time, ΔT. No other operational requirements are made such as specifying the distribution of pulses within the interval ΔT, or designating that the pulses must arrive at the load at a fixed time. The latter requirement is assumed to be controllable by external timing sources.

Using the above model, it is possible to quantitatively determine the individual switch jitter specification imposed by the requirement that the range of the spread be no greater than ΔT. The calculation is performed using the well understood, but generally lesser known methods of order statistics.[3,4,5,6] The complete analysis, which is too complex to present here, can be summarized in the following equation

$$H(\Delta T) = \int_{-\infty}^{\infty} N \left\{ \int_{u}^{u+T} f(x)dx \right\}^{N-1} f(u)du, \qquad (1)$$

where $H(\Delta T)$ is the probability the time spread will be less than ΔT, N is the number of switches, and f(u) is the distribution function of the individual switch closures. If it is assumed that the f(u) is a normal distribution function with standard deviation σ, numerical results can be obtained.[6] Results of calculations for selected values of N are shown in Figure 1.

As an illustration of the procedure used to determine performance requirements, Figure 1 is used to calculate the jitter requirement for each switch used to control the operation of four pulse forming lines within a range of ΔT = 10 ns. Furthermore, it is assumed that satisfactory system performance requires at least 90% of the shots should produce a pulse spread within this range. Referring to Figure 1, the cummulative probability of 0.90 is found to be associated with a ratio of range to standard deviation equal to 3.25, for the N = 4 case. This implies that the individual switches must have a 1σ jitter of 3.1 ns or better, and this was the value chosen as the design goal for the multistage trigatron.

A study of the curves reveal a more increasing stringent jitter requirement for a given operating range ΔT as the number of switches increase. For a pulsed system with a large number of components, the arrival of only one pulse outside the desired time spread ΔT may be acceptable, allowing a relaxation of the switch jitter values obtained in Figure 1. However, for a small number of switched elements, each pulse represents a large percentage of the delivered energy and failure to synchronize in time ΔT would result in a failed shot.

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14. ABSTRACT
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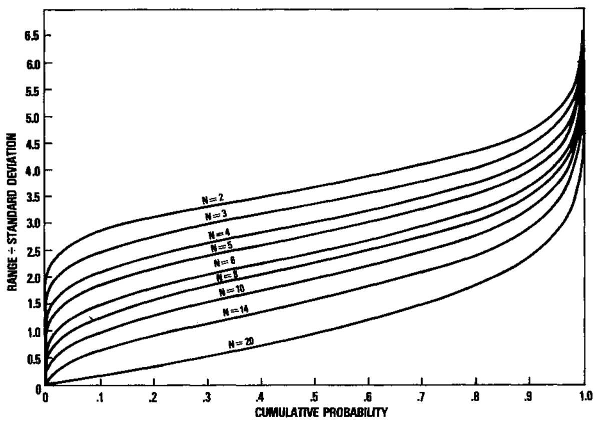

Figure 1. These curves relate the cumulative probability to the normalized range of pulse arrival times for N identical, simultaneously triggered switches. The numerical values are based on switch performance that can be described by a normal distribution with a standard deviation σ.

III. Switch Description and Theory of Operation

The gas switch described in this paper consists of several trigatron sections connected in series; maximum switch voltage is determined by the number of stages and the operating voltage of each stage. For optimum performance, multistage switches require that the applied switch voltage be distributed uniformly between the gaps. Figure 2 illustrates the single gap electrode which incorporates three design features not found in the conventional trigatron.

First, each stage uses a Bruce-profile, uniform-field electrode geometry which differs from the usual hemispherical design.[7] The uniform field gap has the advantage that the maximum field occurs in the region surrounding the electrode axis and is equal to the electrode gap voltage divided by the gap length. This second feature is important in determining a self breakdown voltage that is consistent for each stage and makes it possible to establish a well defined operating point called the M value (M value = self breakdown voltage/operating voltage).[8] In general, command triggering the switch at an M value close to one produces the least switch jitter. On the other hand, the larger the switch M value, while maintaining acceptable jitter, the greater the switch's dynamic range and the less likely the occurance of prefire.

The second feature that distinguishes this switch from most conventional trigatron designs is that the arc contacting surface is made separate from the main switch body. This allows changing of the electrode surface without requiring replacement of the entire Bruce profile electrode. Furthermore, it allows the use of electrode materials, such as carbon, that may have mechanical properties or cost factors which make them unsatisfactory for the entire electrode body. Carbon, arc-contacting surfaces were used in the work presented here, and they exhibited good life with a small amount of surface erosion after 100 shots with no measurable amount of degradation in switch performance. Other materials, such as the PLANSEE K335 copper infiltrated tungsten, are going to be tested for electrode wear at higher currents.

The most unique feature of the series trigatron is that the closure of one gap is used to create a trigger pulse for firing the subsequent gap. In the following, the operational sequence of the switch closure is described.

The first switch gap is command fired from an external source which produces a fast rising, positive voltage pulse on the trigger pin that is coaxially located in the positive electrode. This produces a low current discharge between the trigger pin and the positive electrode which both illuminates and rapidly over-voltages the anode-cathode gap. Prompt streamer formation bridges the main gap; closing the first switch stage. Because the cathode of the first switch section is isolated from the anode of the second, the first stage closure creates a voltage pulse on the trigger pin of the second gap; refer to Figure 2. Once the trigger pin of the second stage arcs to its anode, the second stage closes and the multistage switch "erects" in sequence from the positive end of the switch forward. After the switch closure, the increasing current in the trigger pin produces an inductive voltage drop sufficient to cause multi-channel flashover of the insulating surface at the electrode periphery. Time integrated photographs of the switch operation clearly show both the main gap closure and the secondary insulator flashover.

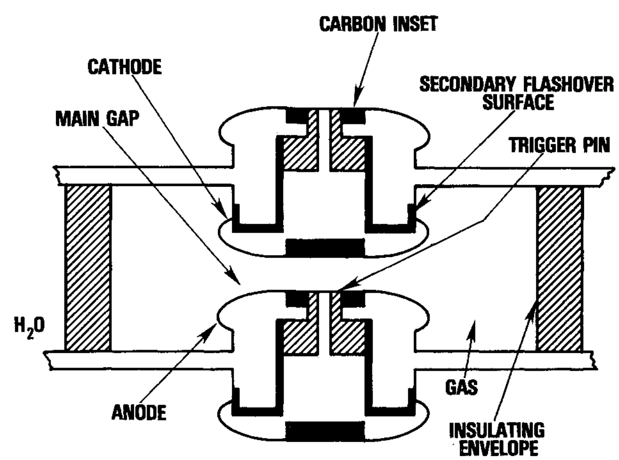

Figure 2. Single stage of multistage trigatron, gas switch. Electrode surfaces follow Bruce prescription for uniform field geometry.

In order to check the theory of operation outlined above, tests were conducted with (1) trigger pins removed from the latter stages, and (2) the anode-cathode insulator removed. Switch delay and switch jitter exhibited a four fold increase in both cases. Additional tests revealed that the trigger pin-anode gap breakdown does precede the insulator flashover as was predicted.

IV. Switch Test Procedures and Results

Initially, one and two stage switches were operated on a "table top" test stand. The purpose of these experiments was to characterize the hardware performance in a highly controlled environment. By shortening the electrode gap it was possible to operate at E/P (electric field/pressure) values similar to those occuring in a working switch stressed to 400 KV per stage. In these tests, it was confirmed that the Bruce profile electrodes gave a well defined breakdown voltage consistent (within 1 percent) with that of accepted uniform gap data.[9] In addition, the two stage switch was command fired with jitter in the <2 ns range for a M value of 1.25.

Next, a six stage switch was installed in a high voltage test stand. This switch was connected to a 4.5 nF water capacitor that was resonantly charged in 1.5μ sec by a 2.7 MV, 15 kJ Marx generator. The switch output was shorted to ground in order to increase peak current and charge transfer. The switch voltage was measured by a resistive divider, while switch current was monitored by three parallel, self-integrating, Rogowski coils. The switch was command fired with a 100 kV, 35 J trigger generator that produces a 45 ns (10 - 90 percent) risetime voltage pulse.

It was found that the hold-off voltage of the six stage switch was considerably lower than predicted. The self breakdown voltages with an air-SF_6 (80:20) mixture were on the average only 0.93 times that of the Paschen values for air; these values were not increased by low voltage conditioning. This result, which was not consistent with the earlier two stage tests, was attributed to the movement of trigger pins and carbon inserts into the main gap caused by the mechanical shock of previous discharges. Electrostatic field code calculations indicated that a small mispositioning of the trigger pin will cause field enhancement in the gap and will lead to a decrease in voltage hold off. Efforts are underway to improve the mechanical strength of the trigger pins and strengthen the attachment of the arc contacting surface to the main body of the switch electrode.

The six stage trigatron has been command fired at slightly over one megavolt, achieving peak currents of 130 kA. Table 1 gives the closure delay and switch jitter as a function of M value. Switch operation below M = 1.35 will give acceptable jitter performance for a four-line system and this operating range should be sufficient to reduce the probability of prefire to a tolerable level.

TABLE 1.
Summary of Jitter Data for
Multistage Trigatron, Gas Switch

M VALUE	%SELF-BREAKDOWN	SWITCH DELAY NS	SWITCH JITTER NS
1.06	94	22.3	4.7
1.33	75	28.1	1.3
1.57	64	63.3	52.5
3.60	28	315	JITTER NOT MEASURED
4.39	23	360	

In summary, the multistage trigatron holds promise for synchronizing multi-line, high voltage, pulse power generators. It will be necessary to mechanically strengthen the switch in order to reach operational status on large systems. Based upon the two stage tests, a factor of two improvement in stage voltage should be possible. Changes in materials and slight modifications in mechanical design are being considered. Moreover, electrodes without triggers are being manufactured for use in the final switch sections; it is hoped that low jitter performance can be maintained in these sections by simple over voltaging. This would reduce the complexity of these electrodes and make them less susceptible to damage.

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